Dynamic Nuclear Polarization in the Fractional Quantum Hall Regime

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We investigate dynamic nuclear polarization in quantum point contacts (QPCs) in the integer and fractional quantum Hall regimes. Following the application of a dc bias, fractional plateaus in the QPC shift symmetrically about half filling of the lowest Landau level, $\nu = 1/2$, suggesting an interpretation in terms of composite fermions. Polarizing and detecting at different filling factors indicates that Zeeman energy is reduced by the induced nuclear polarization. Mapping effects from integer to fractional regimes extends the composite fermion picture to include hyperfine coupling.

An appealing physical picture of the fractional quantum Hall (FQH) effect is the composite fermion model [1], in which an even number, $2m$, of flux quanta ($\phi_0 = h/e$) bind to each electron, creating a composite fermion (CF) that feels an effective field, $B^* = B - 2mn\phi_0$, where B is the applied field perpendicular to the plane of the electron gas, and n is the electron density. The effective field quantizes the CF energy spectrum into the analogue of electronic Landau levels; the FQH effect becomes the integer quantum Hall (IQH) effect of CFs. At filling factor $\nu = 1/2$, corresponding to $B^* = 0$ for CFs with two attached flux quanta ($m = 1$), the CFs form a Fermi sea that can have ground states with different degrees of spin polarization [2, 3]. Composite fermions at other filling factors also have non-trivial spin-polarized ground states. For example, $\nu = 2/3$ ($\nu_{CF} = -2$) and $\nu = 2/5$ ($\nu_{CF} = 2$) have been observed to have both spin-polarized and spin-unpolarized ground states [4, 5].

Dynamic nuclear polarization (DNP) has been used to investigate both the IQH and the FQH regime using transport measurements [3, 6–21]. In both regimes, electron spin flips are accompanied by opposite nuclear spin flops. For instance, in gate-confined GaAs microstructures in the IQH regime, Wald *et al.* [6] found that scattering from the lowest (spin-up) Landau level to the second (spin-down) Landau level flops a nuclear spin from down to up, which in turn increments the Overhauser field, B_N, opposite to the applied field, B. The resulting reduction in total effective Zeeman field was then detectable in transport through a quantum point contact (QPC) [6]. Dynamic nuclear polarization in a QPC with only Zeeman splitting has also been observed [22]. In bulk two-dimensional (2D) geometries, breakdown of the IQH and FQH effects at high bias can also induce DNP [12, 13, 16, 18, 20, 21]. In this case, the direction of the resulting Overhauser field depends on experimental details. In the FQH regime, much of the work—in bulk and in microstructures—has focused on $\nu = 2/3$ [9–11, 15], where DNP is attributed to spin-flip tunneling between spin-unpolarized and spin-polarized domains. Bulk 2D studies using DNP and nuclear relaxation at $\nu = 1/2$ were used to investigate the degree of spin polarization

of the metallic CF state as a function of applied field [3, 17, 19]. Despite the extensive literature on this topic, on both bulk and confined devices, no explicit connection between DNP in the IQH and FQH regimes—creation or detection—has been drawn to our knowledge.

In this Letter, we experimentally investigate DNP in a gate-defined QPC, and identify surprising correspondences between the IQH and FQH regimes, which we then interpret within a composite fermion picture. In contrast to the situation in bulk FQH systems, where DNP may change the spin configuration at a given filling factor, we find that DNP in the vicinity of a QPC can evidently induce changes in density (hence local filling factor) within the constriction. Resistance plateaus as a function of B in both IQH and FQH regimes shift and change in length following application of a nonzero dc bias. Using resistively detected nuclear magnetic resonance (NMR), we demonstrate that the applied bias induces nuclear polarization. Interestingly, the pattern of shifting plateaus is symmetric about the the half-filled first Landau level, $\nu = 1/2$. Comparable shifts are also found in the IQH regime. We then determine the sign of the induced Overhauser field to be opposed to the ap-
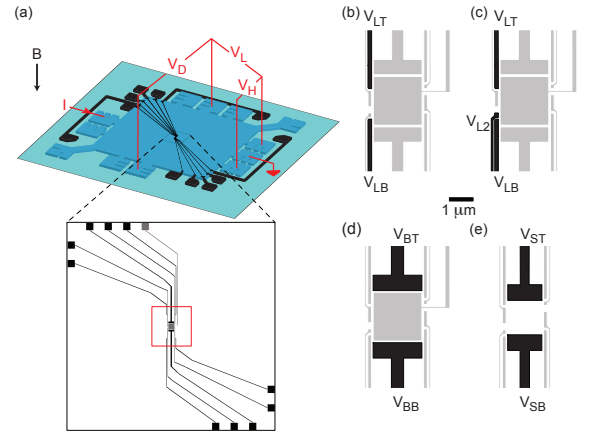

FIG. 1: (a) Device layout, showing leads used for current bias I and diagonal voltage, ν_D, as well as bulk longitudinal and Hall voltages. (b-e)Gate layouts for 1 μm, 750 nm, 2 μm, and 1.4 μm constrictions, indicating depleted (black) and grounded (gray) gates.

plied field in all cases, and estimate the magnitude of the Overhauser field by observing its effects at large filling factors, where the Overhauser field can exceed the applied field and effectively reverse the sign of the Zeeman field. Finally, we interpret related DNP effects in the IQH and FQH regimes in terms of simple Zeeman-split CF edge states.

Measurements were carried out on four devices [Figs. 1(b-e), black gates depleted], all showing similar behavior. Data presented are from devices in Figs. 1(b,c). The devices were fabricated on a two-dimensional electron gas (2DEG) in a symmetrically Si-doped GaAs/AlGaAs 48 nm quantum well structure located 400 nm below the wafer surface with density $n = 7.8 \times 10^{14}$ m^{-2} and mobility $\mu = 1,300$ m^2/V·s measured in the dark. Similar behavior was observed on a different wafer with roughly twice the density. Square mesas were wet-etched [Fig. 1(a)], and Ti/Au (5 nm/15 nm) surface gates were patterned using electron-beam lithography. Depleted gates except V_{L2} were set to ~ -1.5 V. Gate V_{L2}, when used, was set to ~ -0.8 V. Other gates were grounded.

Measurements were made using a current bias I, with dc component, I_{DC}, up to 100 nA and ac component 400 pA at 153 Hz. The electron temperature was $\sim$50 mK. We typically measure the diagonal voltage, V_D, which is the voltage difference between incoming edge states on opposite sides of the QPC. Lock-in measurements of the diagonal resistance, $R_D \equiv dV_D/dI$, were used to determine the local filling factor in the QPC, $\nu_D \equiv h/R_D e^2$. Two procedures were used to apply I_{DC} to the QPC. In the first procedure ("holding"), I_{DC} was set to a value I_{hold} for a time t_{hold} before being set back to 0. Unlike in less symmetric geometries [12], results did not depend on the sign of I_{hold}. In the second procedure ("sweeping"), I_{DC} was swept from a positive value (I_{max}) to a negative value ($-I_{max}$) and then swept back to 0; sweep direction made no difference. The two procedures lead to similar overall behavior, as well.

Figure 2(a) shows R_D as a function of B and I_{DC} in the 750 nm constriction [Fig. 1(c)], acquired using the sweeping procedure at each field then stepping the field downward. Comparing zero-bias data taken prior to sweeping (red) with the zero-bias cut through data (black) shows that sweeping causes the $\nu_D = 1/3$ plateau to extend to lower field, just past the high-field edge of the $\nu_D = 2/5$ plateau in (red) data taken prior to sweeping I_{DC} (red). The transition region between $\nu_D = 1/3$ and $\nu_D = 2/5$ becomes abrupt after sweeping dc bias; in the prior data, the transition is seen to be gradual. Figure 2(b) shows similar extensions of plateaus for ν_D between 2/5 and 2/3 in the 1 μm constriction [Fig. 1(b)]. Here, the bias was applied using the holding procedure at each field, then the field stepped downward. The black trace shows R_D immediately after the return to zero dc bias at each field while the red trace was measured with no dc bias applied.
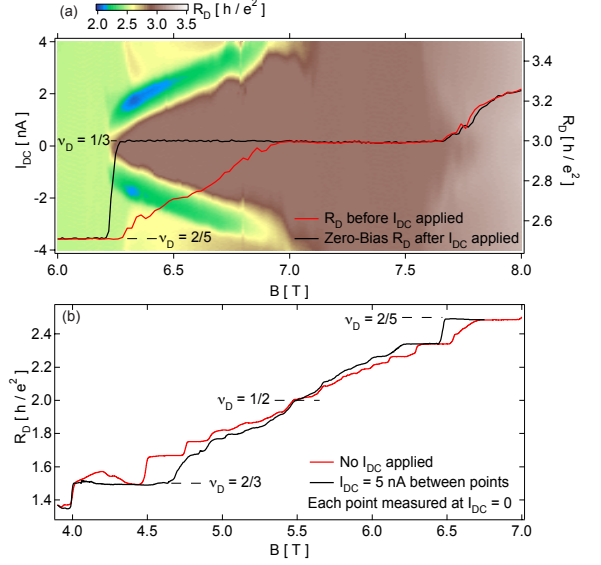

FIG. 2: (a) Diagonal resistance of the QPC, R_D, (Colorscale) as a function of B and I_{DC} (left scale) in the 750 nm constriction. Traces (right scale) show R_D at $I_{DC} = 0$ as a function of B before (red) and after (black) application of I_{DC}. Black trace is the zero-bias cut through the color plot. (b) R_D as a function of B in the 1 μm constriction before (red) and after (black) application of $I_{DC} = 5$ nA.

The pattern of shifts and extensions of plateaus of R_D [Fig. 2(b)] exhibits a striking symmetry about $\nu_D = 1/2$: applying then removing dc bias at each field causes all plateaus to shift toward $\nu_D = 1/2$, which, as a symmetry point, does not change position [23]. Bulk Hall and longitudinal resistances do not exhibit any change in behavior after applying I_{DC}.

Similar shifts and extensions of plateaus occur when the bias is applied at a different filling factor from where its effects are observed. Changes in filling factor can be accomplished by either changing field or QPC gate voltage. This is illustrated in Figs. 3(a-c), which show R_D as a function of time, measured at the same field and gate settings, following application of I_{DC} at three different filling factors. Field and gate voltages were first set to give a well-quantized $\nu_D = 3/5$ plateau in the 1 μm constriction prior to application of I_{DC}. Then, either field or gate voltage was used to change ν_D, where dc bias sweeping procedure was applied. Field or gate voltage values were then returned to the settings where $\nu_D = 3/5$ was originally observed. In all cases—regardless of where I_{DC} is applied—after a transient (due to residual heating from I_{DC}) R_D settles at a value indicating $\nu_D = 2/3$ for tens of minutes before suddenly returning to its original $\nu_D = 3/5$ value.

Plateau shifting with characteristic symmetry about $\nu = 1/2$ is also observed when I_{DC} is applied at a single filling factor rather than at each value of B. In Fig. 3(d), the I_{DC} sweeping procedure applied once, just below $\nu = 1/3$ ($B = 7.5$ T), before sweeping field downward

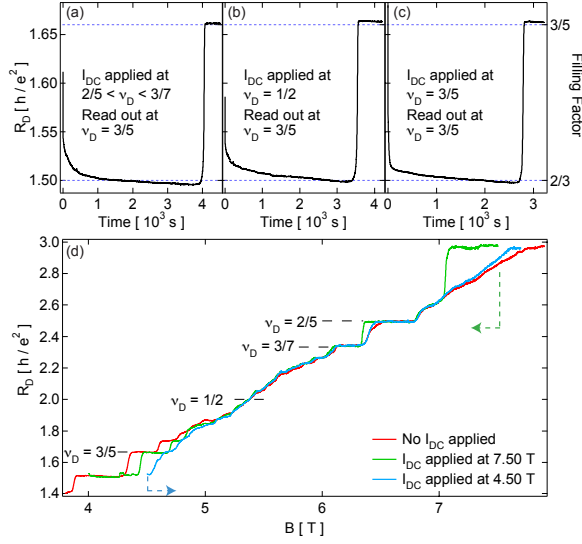FIG. 3: (a-c) R_D as a function of time measured in the 1 μm constriction at $\nu_D = 3/5$ after $I_{DC} = 10$ nA was applied at (a) $2/5 < \nu_D < 3/7$, (b) $\nu = 1/2$, and (c) $\nu_D = 3/5$. (d) R_D as a function of B in the 1 μm constriction. Red trace indicates R_D before I_{DC} has been applied. Green trace indicates R_D after $I_{DC} = 20$ nA has been applied at $B = 7.50$ T. Blue trace indicates R_D after $I_{DC} = 34$ nA has been applied at $B = 4.50$ T.

FIG. 4: (a-c) R_D as a function of f_{NMR} in the 1 μm constriction at $B = 7.50$ T, 4.60 T, and 1.29 T. [24] (d,e) R_D as a function of B in the 1 μm constriction. Red trace indicates R_D before I_{DC} has been applied. Green trace indicates R_D after $I_{DC} = 54$ nA has been applied at $B = 1.22$ T. Blue trace indicates R_D after $I_{DC} = 95$ nA has been applied at $B = 0.70$ T.

to $\nu = 2/3$ ($B = 4.0$ T) with I_{DC} at zero. Symmetry about $\nu = 1/2$ is evident despite the asymmetry of where the dc bias was applied. Similar behavior is seen when I_{DC} is applied once at $\nu = 3/5$ ($B = 4.5$ T) before sweeping the magnetic field upward toward $\nu = 1/3$ ($B = 7.8$ T) with $I_{DC} = 0$ [Fig. 3(d)]. From these data, we conclude that the observed symmetry about $\nu = 1/2$ reflects the *response* of the system to a common, roughly field-independent, physical mechanism.

The slow relaxation seen in Figs. 3(a-c) suggests DNP as the origin of the effects of applied bias. This is confirmed using resistively detected NMR. Following sweeping application of I_{DC}, an ac magnetic field pulse at frequency f_{NMR} is applied using a six-turn coil that orients the ac field predominantly in the plane of the electron gas. When f_{NMR} matches one of the expected NMR frequencies, R_D returns to the value measured before applying I_{DC}. Figures 4(a,b) show depolarization signatures in R_D for ^{75}As NMR at $\nu_D = 1/3$ and $\nu_D = 3/5$. Similar signatures are also observed for ^{69}Ga and ^{71}Ga NMR frequencies (not shown).

Following DNP at $\nu_D = 3/5$, ramping the field to the edge of the $\nu_D = 1$ plateau causes all plateaus to return to their unpolarized positions. This rapid depolarization can be understood by the presence of skyrmions near $\nu = 1$, which are known to cause relaxation of nuclear polarization [25–27].

At lower fields, plateau shifts and extensions in the IQH regime are seen following DNP from I_{DC} applied between (not directly on) IQH plateaus. Following DNP,
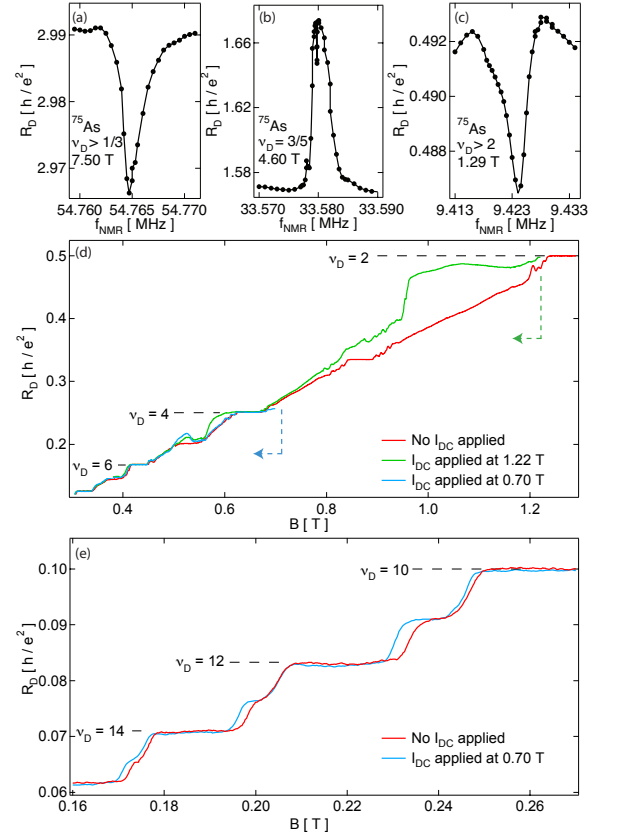
spin-split plateaus at $\nu_D = 3$ and $\nu_D = 5$ disappear for several minutes [Fig. 4(d)]. NMR confirms the DNP interpretation [Fig. 4(c)]. The sign and magnitude of the Overhauser field can also be deduced in the IQH regime. For B_N along B, ($B_N > 0$), spin splitting will always increase with DNP; for B_N opposing B, spin splitting will decrease for mild DNP, reach zero for $|B_N| = B$ and again increase when $|B_N| > B$ (with reversed spin splitting). Comparing Figs. 4(d,e), we see that for $B \sim 0.5 - 1$ T, the odd (spin-split) plateaus are weakened by DNP, whereas for $B \sim 0.2$ T, odd plateaus are enhanced by DNP. We conclude that B_N induced by DNP is directed opposite to B and is between 0.2 and 0.5 T in magnitude.

To connect DNP effects between IQH and FQH regimes, we polarize in the one regime and read out in the other. For instance, we apply I_{DC} using the sweeping procedure at $\nu_D = 2$, followed by ramping to a value of field where $\nu_D = 3/5$ before polarization. Depolarization from skyrmions upon passing through $\nu_D = 1$ are avoided by fully depleting the QPC during the field ramp. We find that R_D initially indicates $\nu_D = 2/3$ value before sharply returning to the $\nu_D = 3/5$ value after several

minutes. Reversing the order—polarizing at $\nu_D = 3/5$ and reading out at $2 < \nu_D < 3$—yields analogous results. We conclude from both procedures that the direction of induced Overhauser field opposes the applied field in both IQH and FQH regimes. We also conclude that the relevant DNP occurs in the QPC (not downstream) since depolarization by skyrmions was eliminated by depleting only the electrons in the QPC constriction.

In the IQH regime, DNP presumably occurs by spin-up electrons at high-bias entering the QPC flipping into empty spin-down states, accompanied by a nuclear flop from spin down to spin up. Because dc bias exceeds Zeeman splitting but not cyclotron energy, the opposite mechanism, involving flip-flop spin relaxation between different Landau levels, which would would tend to align B_N and B, does not occur.

Evidently, a similar mechanism appears to occur in the FQH regime. Within a CF picture, even filling factors can have spin-unpolarized ground states while odd filling factors are always at least partially polarized [1]. Hence, similar to electrons, CFs can be excited from a spin-up to a spin-down state. Within this model, for example, exciting CFs from a spin-up subband of $\nu = 3/5$ ($\nu_{CF} = -3$) to a spin-down subband of $\nu = 4/7$ ($\nu_{CF} = -4$) will result in $B_N < 0$. Excitations from spin-down to spin-up states may also be possible, however, since the CF Zeeman energy is comparable to the CF cyclotron energy [1].

We interpret the effect of B_N on plateau structure as depending on ground-state spin configurations at successive filling factors. If successive states have different degrees of spin-polarization, B_N will change the length of the associated plateaus; if successive states are both spin-polarized, then B_N will shift plateau positions. In the IQH regime, odd filling factors are spin-polarized while even filling factors are spin-unpolarized, hence B_N causes plateaus at even filling factors to lengthen at the expense of plateaus at odd filling factors. In the FQH regime, the more spin-polarized state will also be destabilized by B_N, leading to a shorter plateau. We observe the destabilization of more spin-polarized plateaus in favor of less spin-polarized plateaus in both regimes: at $3/5 \leq \nu_D \leq 2/3$ ($-3 \leq \nu_{CF} \leq -2$) in Fig. 2(b) in the FQH regime and at $2 \leq \nu_D \leq 3$ in Fig. 4(d) in the IQH regime. The changes in the lengths of the plateaus observed in Fig. 2(b) are analogous to those observed in Fig. 4(d), suggesting that CF's in the FQH regime are exhibiting the same behavior as electrons in the IQH regime. Within this picture, shifts in plateau position can only occur in the FQH regime, where successive states can both be spin-polarized. A change in Zeeman energy will not affect the size of the gap between spin-polarized CF Landau levels but will shift the energies of the levels equally. When the Zeeman energy is decreased, the energy of each spin-polarized level increases, causing a local depopulation of electrons in the QPC. Each energy level will then be filled at a lower magnetic field; the start of each plateau will then appear at a lower field than before DNP. We observe this shifting of the plateaus at $1/3 < \nu < 2/5$ [Fig. 2(a)]. Finally, while DNP is found to readily occur at $\nu_D = 1/2$, it leaves little or no signature in R_D at $\nu_D = 1/2$, by symmetry, but can be observed by moving to another filling factor after DNP, as seen in Fig. 3(b).

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[23] On the high-field side of the symmetry point ($\nu_D < 1/2$) shifts and extensions of plateaus require that the bias is applied between plateaus, while on the low-field side ($1/2 < \nu_D < 2/3$) shifting occurs regardless of where I_{DC} is applied.
[24] The expected NMR frequencies for at B = 1.29 T, 4.50 T, and 7.50 T are 9.406 MHz, 33.540 MHz, and 54.685 Mhz, respectively. We attribute this difference to a slight offset in zero value of our magnet, equal to roughly 8 mT at zero field.
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